COOPERATIONAL ASSESSMENT OF MINE WASTE ROCK FOR REMEDIATION AND REUSE[1]

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Abstract. A legacy of waste rock associated with abandoned mining operations continues to degrade water quality in the Colorado Front Range. The success of remediation at these sites may be impeded by financial constraints, uncertain liability, and the legal status of lands in question. However, the development of safe, cost-effective reuses for orphan mine wastes may offset remediation costs and encourage stakeholder participation. Service-based, experiential education adds value to the effort, allowing undergraduate students to provide preliminary assessments of mine waste while interacting with nonprofit and consulting organizations. To investigate the feasibility of this approach, collaboration among the nonprofit Clear Creek Watershed Foundation, Colorado School of Mines, and Frontier Environmental Services, Inc., examined waste piles along Trail Creek, near Idaho Springs, CO. Piles were assessed for impact on the surrounding watershed and for potential reuse as foundational concrete aggregate for a proposed local wind farm. Grab samples and 30-subsample composites were evaluated according to established physical and chemical criteria. Physical data gathered included volumetric assessments of the piles, sieving to compare particle size distributions to ASTM aggregate standards, and ranking of each site according to distance to drainage, erosion, and vegetation present. Concentrations of metals regulated by EPA maximum contaminant levels (MCLs) were analyzed in leachates by ICP-AES and compared to regulatory limits. Slag material had sufficient coarse aggregate content for concrete applications (ASTM standards), while unprocessed waste rock, which comprised most of the material available, contained an excess of fines. Regarding chemical leachability, both waste rock and slag were found to be acceptable for landfill disposal with the exception of isolated lead measurements exceeding hazardous waste regulations. Over the investigated reach of Trail Creek, total metal loading increased by 4.8 kg/day proximal to the piles, suggesting that removal could alleviate the metal burden (particularly Zn and Cu) on receiving waters.

Additional Key Words: Brownfields to Brightfields Initiative, byproduct reuse, sustainable reclamation, educational outreach

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Introduction

In the spirit of the EPA/DOE Brightfields Initiative (U.S. EPA, 1999), which promotes the use of Brownfields for renewable energy projects, three sites along Trail Creek near Idaho Springs, CO (Dumont Placer, Gumtree, and Jones Slag Placer) were identified as waste piles that could potentially be used as construction materials for alternative energy projects.

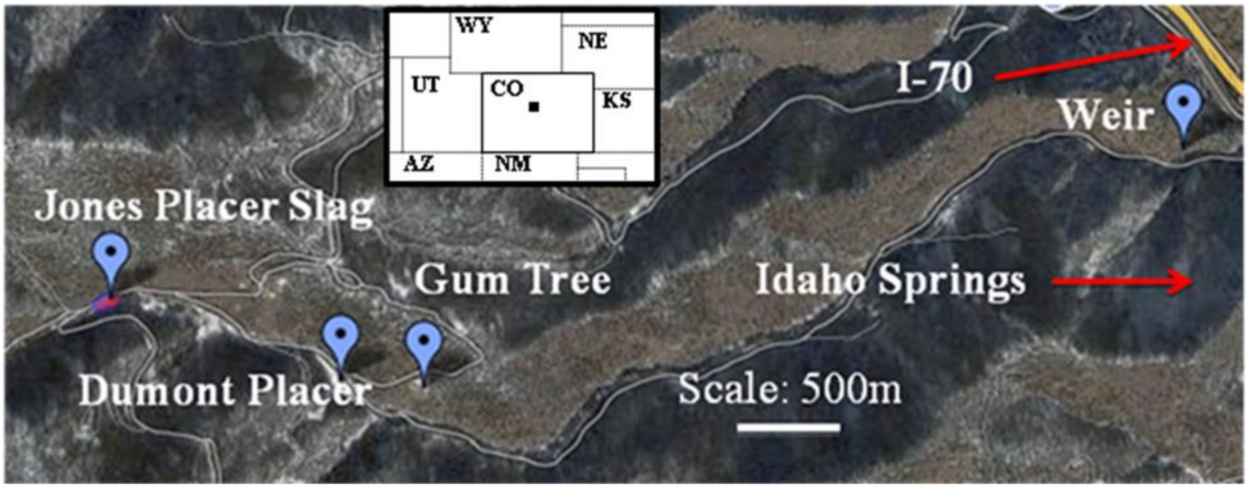


Figure 1. Local map of three waste piles along Trail Creek that were selected for this study (adapted from googlemaps.com)

As seen in Figure 1, these piles are located on Trail Creek Road just west of Idaho Springs, Colorado. The section of Trail Creek under study spans latitude N39°44.288' to N39°44.493' and longitude W105°35.300' to W105°35.796'. All three sites were within one square mile. While Upper Trail Creek is already the site for a Clean Water Act (CWA) Section 319 grant, the lower section of Trail Creek is riddled with other non-point sources of heavy metals and acid-forming mine waste (AFMW), and so is under scrutiny for future remediation. Clear Creek Watershed Foundation (CCWF), who has been contracting water quality surveillance for Trail Creek since at least 2006, received a technical report concerning Trail Creek water quality from Mike Crouse of Clear Water Consultants in February 2010, revealing that levels of Cu and Zn were below 2006 – 2009 chronic water quality standards. However, lower chronic water quality standards came into effect at the close of 2009, rendering all measured Cu and Zn values in excess of the new standards. Wastes from mining operations at the nearby Lamartine and Freeland mines are known to have been added to the Dumont Placer and Gumtree waste piles and to have contributed to stream loading of Zn and Cu, respectively. (Crouse 2010)

There are several purposes for this paper. First, it will be shown how simple physical and chemical techniques that are normally used to assess hazardous materials (Wildeman *et al.*, 2007) can be used to give an indication of whether waste rock can be used safely as recycled materials in future construction projects. Secondly, it will be shown how experiential, community-based educational modules that pair students with local organizations can promote engagement for students who are enrolled in fields focusing on natural resources. In a broader perspective, this effort aimed to bring value to these sites in the form of collaborative science and engineering, experiential undergraduate education, and by evaluating the waste for potential reuse. In doing so, the project also contributed to progress in regional environmental objectives. In collaboration with CCWF, both Frontier Environmental (FE) and Colorado School of Mines (CSM) conducted field and laboratory assessment of the three waste piles and the portion of Trail Creek that flows by the piles. This preliminary, non-regulatory assessment conducted by CSM was used to focus an official assessment and report by FE for use by lending agencies and contractors for determining project feasibility. Thirteen students were divided into three groups, each of which was assigned to handle sampling and data analysis for one of the three sites. The scientific objectives of the field and laboratory assessment were:

1. To provide a preliminary indication of whether or not pile materials could be used as aggregate in concrete used in the foundation of proposed wind turbines in the region.
2. Assess which of the piles would be most feasible for use as concrete aggregate.
3. Assess whether the waste materials could be used as backfill at alternative energy sites if it wasn't suitable for aggregate.
4. Based on local hydrological conditions and type of rock (waste rock or slag) estimate the relative contributions that each pile has on metal loading in Trail Creek.

Materials and Methods

Sample Collection

Students were divided into groups and assigned to waste piles Dumont Placer (Fig. 2), Gumtree and Jones Placer Slag on May 18th, 2010 for field assessments and sampling. To secure a representative sample, composites consisting of thirty-subsamples were collected from subunits on a standardized grid of each pile, and then were dried, sieved and subjected to the battery of leaching procedures described below for a sample mean representative of each pile (Smith et al., 2000). Water samples were also collected along Trail Creek proximal to the three piles, and ionic conductivity and pH were measured on each sample at the time of collection. Flow rates were subsequently estimated by several methods including tracer and float tests (Day 1977) in the field on May 21st, 2010, which could be considered a typical spring runoff day.

Figure 2. Dumont Placer Waste Rock

Physical Assessments

Field criteria that were used to assess Dumont Placer, Gumtree, and Jones Slag Placer experimental sites are listed in Table 1. Piles were ranked by students according to criteria established for use in evaluating potential aquatic toxicity from AFMW (Wildeman *et al*. 2007). Each site received ratings on a 1-5 scale for separate, semi-quantitative parameters (distance to drainage, erosion, surrounding vegetative growth (kill zone), and vegetation on pile) relating to overall physical stability of the waste piles. Physical hazards may be present with or without chemical hazards, and so each must be considered independently to achieve the most accurate assessment possible.

Students estimated the volume of each pile using simple geometric shapes for different pile sections. Distances were determined with laser distance scopes and tape rules and relevant slope angles with inclinometers. Planar approximations for surfaces were used to approximate volumes. To compare particle size distributions to ASTM C33 standards for concrete aggregate, (ASTM 2006) soil samples were sieved sequentially with 12.7 mm (½"), 9.51 mm (3/8"), 6.35 mm (1/4"), 2.38 mm (Tyler mesh no. 8), 1.00 mm (#16), 0.152 mm (#100), and 0.074 mm (#200) sieves.

Table 1. Criteria used for physical assessments of the three waste sites along Trail Creek west of Idaho Springs, CO.

Ranking	Distance to Drainage	Erosion	Vegetation on Pile	Vegetative Kill Zone
1	> 300 m	none	vegetation prevalent	kill zone not present
2	> 100 m	sheet wash	vegetation present	NA
3	> 30 m	rills < 15 cm deep	little vegetation	very little kill zone
4	< 30 m	rills 15 - 30 cm	NA	trees but no underbrush
5	< 3 m	rills > 30 cm	no vegetation present	extensive kill zone

Hydrological Assessments and Metal Loading Calculations

To adjust for dilution effects and changes in flow along Trail Creek, flow rates were determined at three successive locations using weir calculations, Manning's Equation for open-channel flow (1), tracer tests, and float tests. These values were used to assess changes in flow along Trail Creek. To account for dilution effects in metal loading calculations, ICP-AES data was used in conjunction with the flow data gathered to calculate metal loads.

$$\text{Manning's Equation:} \quad Q = n^{-1}AR^{2/3}S^{1/2} \qquad (1)$$

Where: Q = discharge (m^3/s)

A = cross sectional area (m^2)

n = Gauckler-Manning coefficient (no units)

R = hydraulic radius (m)

S = slope of the water surface or the linear hydraulic head (m/m)

Metal loads were calculated by multiplying discharge by total metal concentration.

$$\text{Metal Load (mg/s)} = Q\ (\text{L/s}) * C\ (\text{mg/L}) \qquad (2)$$

Laboratory Assessment Activities and Experimental Procedures

To provide a preliminary assessment as to whether the waste piles might serve as concrete aggregate or backfill material for alternative energy projects, the sites were ranked for physical stability and subjected to five separate leach tests to detect the potential for release of toxic metals. The tests were designed in order to evaluate contaminant release due to different environmental stressors such as acid rain (Synthetic Precipitation Leaching Procedure (SPLP) EPA Method 1312,(U.S. EPA 1994), organic acids in landfill conditions (Toxicity Characteristic Leaching Procedure (TCLP) EPA Method 1311, (U.S. EPA2002), release of pyritic sulfides from H_2O_2 (Net Acid Generation, or NAG test), and exposure to natural water at two different liquid-to-solid ratios (United States Geological Survey (USGS) Field Leach Test, and Colorado Department of Minerals and Geology, (CDMG) Leaching Test (Wildeman *et al*. 2007).

Chemical Assessments. Using the Mine Waste Decision Tree (MWDT) (Wildeman *et al*. 2007) in Fig. 3 as a guideline, the students conducted several leaching tests to gauge the potential for dissolution of pyritic sulfide minerals and other relevant factors. In accord with the MWDT, students assumed ecological toxicity due to enhanced solubility of trace metals if the leachate pHs were less than 5.0. Samples with natural water leachates pHs above 5 were tested to determine more thoroughly if the waste could be expected to leach toxic elements if used as concrete aggregate or backfill for alternative energy projects.

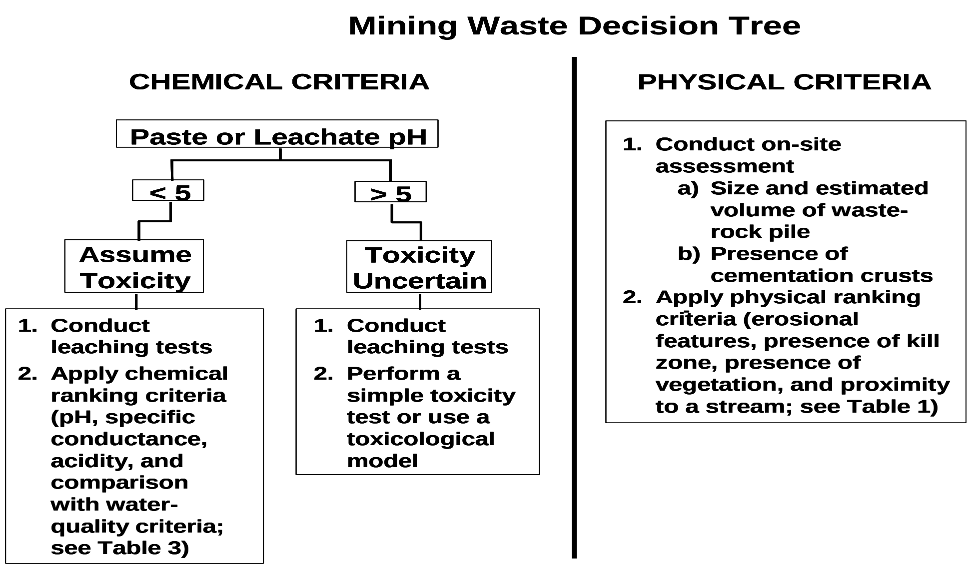


Figure 3. The Mine Waste Decision Tree from Wildeman *et al.* 2007

Leaching Procedures. The USGS Field Leach Test (Hagemann and Briggs, 2000, Hagemann 2005) uses 50 g of <10 mesh material to 1 L deionized water (DI) water, followed by 5 minutes of shaking and 10 minutes of settling. After 10 minutes of settling, the students measured specific conductance and pH. For the (CDMG) leaching procedure, students retained the -10 mesh material and added 300 mL DI water to 150 mL of sample. After shaking for 15 seconds in a 800 mL polyethylene bottle, the sample was allowed to settle for 90 minutes. The modified TCLP, similar to EPA Method 1311 (U.S. EPA, 2002), employs an extraction fluid composed of a dilute mixture of glacial acetic acid and NaOH, pH 4.93 ± 0.05. A 40 mL volume of this extraction fluid was added to 2.00 g <80 mesh sample in a 125 mL bottle. These bottles were then agitated for 18 hours using a rotary tumbler. The SPLP (EPA Method 1312) determines potential for release of toxic elements released due to acid rain (U.S. EPA, 1994). The NAG test was devised to detect the presence of acid-forming sulfide minerals. For the NAG the students added 40 mL of H_2O_2 to 2.0 g of sample and heated for 30 minutes to detect sulfide minerals and other constituents of the leachate.

The students collected 14 mL of the supernatant from each procedure, filtered the resulting samples (0.45 μm) and acidified with HNO_3 for ICP-AES analyses. The concentrations of 31 elements (Ag, Al, As, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, S [as SO_4^{2-}], Sb, Se, Si, Sn, Sr, Ti, V, Zn, and the Sc internal standard) were determined using a Perkin Elmer 3000 ICP-AES. Students compared these values to a set of regulatory values compiled from available health and ecology-based regulatory limits promulgated by the EPA (MCLs Tier I and II) and the Colorado Department of Public Health & Environment (CDPHE) Water Quality Control Commission Regulation 38 (EPA 2004). From the modified TCLP results, comparison with EPA RCRA regulatory standards indicated whether the mine waste legally constituted hazardous material. The official regulatory TCLP was performed by FE and not the students.

In addition to comparing leachate concentrations with regulatory standards, students compiled elemental concentrations determined by ICP-AES into element concentrations pattern graphs (ECPGs). While leaching procedures varied by extraction fluid as well as liquid to solid ratio (by a factor of ten), elemental concentration patterns were fairly consistent, indicating that ECPGs may give a sound estimate of the relative toxicity potential of the different waste piles.

Results

Three types of assessments were employed to estimate metal loading from the slag and waste rock piles: a) physical assessments to estimate volume and coarse aggregate content of each pile, b) chemical assessments in the form of a battery of five leaching tests and Trail Creek waters analyzed by ICP-AES, and c) hydrological assessments to characterize changes in flow rate and metal loading over the reach of Trail Creek spanned by the three piles. Physical assessments are useful to understand both how much it would cost to move the pile, but also the extent of the resource potentially useful to nearby construction projects. The chemical assessments represented a crucial first step towards quantifying the changes in metal loading along Trail Creek, showing that different types of mining waste may exhibit different effects on downstream metal concentrations. Characterizing the flow rate was necessary to determine a bulk metal loading rate.

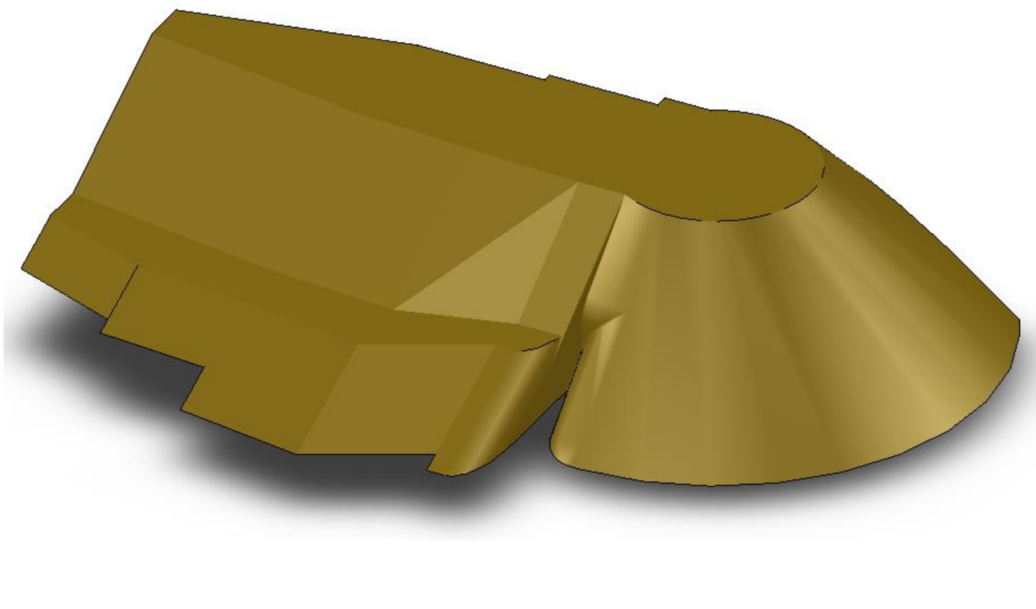
Physical Assessments

Using the physical ranking criteria from the MWDT, the first pile of waste rock (Dumont Placer) showed the most significant potential for metal release to Trail Creek, with maximum ratings in distance to drainage and evidence of erosion (Table 2).

Table 2. Physical assessment and volume estimates of the three sites along Trail Creek.

	Distance to Drainage	Erosion	Vegetation on Pile	Vegetative Kill Zone	Volume Estimate (m^3)
Waste Rock #1 *(Dumont Placer)*	5	5	4	1	13,700 ± 2,000
Waste Rock #2 *(Gumtree)*	3	3	2	1	17,000 ± 2,000
Slag Material *(Jones Placer)*	5	1	2	3	5,500 ± 2,000

Volume Estimates. Participants in the field session estimated the volume of each pile by breaking it up into discrete parcels. The dimensions of these parcels were then determined by laser distance scopes and used to build a visual model for each pile in SolidWorks® (Fig. 4). The resulting calculated volumes were then corroborated with calculations for waste rock volume as shown in Table II. The waste rock piles were both more than double the volume of the slag material.



Scale 50 m
Average Mountain Slope 37°

Figure 4. Student generated depiction of the Gumtree waste rock pile for volumetric calculations (17,000 m^3) using SolidWorks®.

Particle Size Distribution. In Fig. 5, the particle size distribution for the Gumtree waste rock pile is compared with the required distribution for coarse aggregates as prescribed by the ASTM C33 standard (ASTM, 2006). As shown in Fig. 5 for the Gumtree pile, waste rock piles were found to consist of material too fine for direct use as concrete aggregate. However, slag material was too coarse to be sieved accurately.

Figure 5. Gumtree Waste Rock vs. ASTM Standard C33 (ASTM 2006, Vol. 04.02)

Chemical Assessments

Water was sampled at two locations from the Dumont Placer waste rock pile, and no pore or surface water was observed at the Gumtree waste rock pile. This was likely caused by slope aspect, as the Gumtree pile was on the more southern-facing slope. For the waters found on the Dumont Placer pile, the pH was less than 5, which according to the MWDT (Fig. 3) implies that this water should be considered toxic to aquatic organisms. This low pH with SO_4^{2-} levels up to 624 mg/L, strongly indicated the presence of acid forming sulfide minerals. Water from a surface pond on the pile was pH 3.9, and water from a hole that was dug at the edge of the pile, which quickly filled with pore water, measured at pH 3.2. ICP-AES analysis later determined that water samples from this hole contained alarmingly high concentrations of Al (35.6 mg/L), Cd (0.141 mg/L), Cu (23.2 mg/L), Fe (4.1 mg/L), Mn (18.1 mg/L), SO_4^{2-} (623 mg/L) and Zn (17.3 mg/L). These metal concentrations were higher than any obtained through leaching procedures, suggesting that leaching procedures may underestimate acid mine drainage effects on the surrounding watershed. Water samples taken along lower Trail Creek suggest that metal loading does not increase downstream of the Jones Placer slag pile, and so the slag material is not a likely threat to stream ecology. However metal loading does increase below the waste rock piles. Indeed water from a roadside gully that runs along the toe of the Dumont Placer pile, (seen in Fig. 2) has a pH of 4.5. This supports the hypothesis that acid-forming sulfides do indeed pose a threat to aquatic ecology and that removing these materials could reduce strain to downstream biota.

The two waste rock piles exhibited higher leaching potential than the slag material for all metals analyzed. CDMG leachates of composites from the two piles of waste rock contained similar levels of Al, Ba, Cd, Cu, Fe, Ni, SO_4^{2-}, and Zn. The average concentration of Mn was significantly higher ($P < 0.1$) at the Dumont Placer (3.2 ± 1.4 mg/L than the Gumtree (1.2 ± 0.9 mg/L waste rock pile. Conversely, Pb concentrations were significantly higher ($P < 0.05$) in CDMG composite samples from the Gumtree pile (0.99 ± 0.54 mg/L) than the Dumont Placer pile (0.16 ± 0.2 mg/L). Modified TCLP leachates from the Gumtree pile yielded one measurement of Pb concentrations in excess of the 5 mg/L RCRA limit. This has been found on other waste rock piles, and is usually attributed to the presence of anglesite ($PbSO_4$) (K. Smith, personal communication). Large variance in data gathered from the Gumtree waste rock pile, combined with another > 5 mg/L result for one SPLP leachate suggest that there are localized sources of Pb that will most likely not cause the waste rock to be classified as hazardous, but the data suggest that some quantities of potentially mobile Pb do exist in this pile of waste rock. Field-scale variations in mineral composition may be at least partially responsible for the differences noted between the two piles, but other factors such as increased snowmelt from solar radiation on the south-facing slope may also play a role in regulating Pb-related biogeochemical processes.

Estimating Flow Rates and Metal Loading Calculations

As shown in Fig. 6, total metal loading increased along the studied reach of Trail Creek suggesting that the waste rock piles are probably responsible for the additional loading. Removal of one or more of the waste rock piles is likely to reduce that load, once steady state conditions have resumed after the initial physio-hydrological disturbance of removing the pile(s). Water quality surveillance revealed that in average low-flow conditions, Trail Creek flows at 0.014 m^3/s (0.5 cfs), while storm events can bring flows up to 0.17 m^3/s (6 cfs) (Crouse 2010). The average flow rate determined by field session participants of 0.053 ± 0.024 m^3/s (2 cfs). is within these extremes.

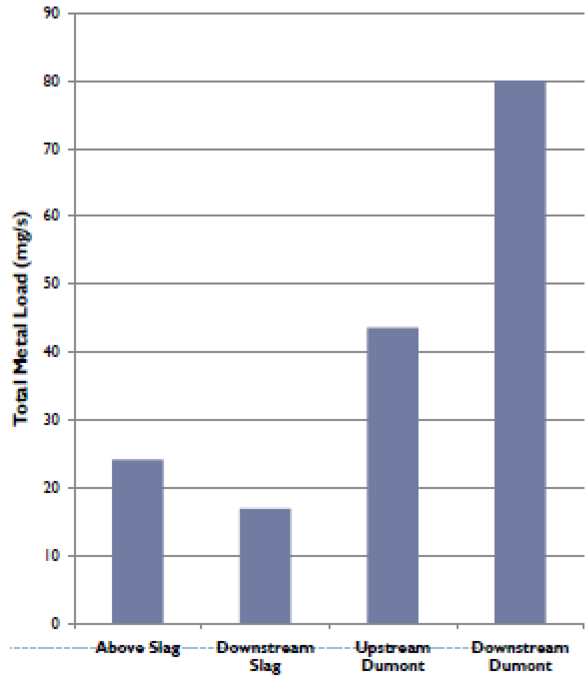


Figure 6. Metal loading along Trail Creek

Discussion

A synthesis of the gathered data suggests that, of the three piles, Dumont Placer is the most feasible to remediate. The physical and chemical analyses suggest that waste rock may be usable as concrete aggregate; provided that ASTM's coarse aggregate requirement is satisfied through mixing with an external source of coarse aggregate. While the use of local sources is generally most efficient, the partnership between Frontier Environmental and the Clear Creek Watershed Foundation makes it possible for CCWF to capitalize on cost-effective remediation, while FE has the opportunity to take advantage of the reduced transportation costs involved with using local construction materials.

Comparing the three piles, Dumont Placer was the most impacted by erosion, ranking highest in overall risk by the physical criteria ranking protocol provided. It must be noted that Pb concentration in modified TCLP leachates from the Gumtree waste pile were over the 5 mg/L RCRA limit in one of three samples, suggesting heterogeneity in lead concentrations that could impede the use of this material for fill. This, combined with comparatively difficult access to the Gumtree waste pile across Trail Creek and its location, ~100 m above any passable roads, suggest that again the removal of Dumont Placer waste would be the most feasible option for use as concrete aggregate or backfill. Depending on the relative costs of local processing compared to the transportation of suitable coarse aggregate to satisfy ASTM standards of a mixture, the slag material may or may not also represent a potential solution to satisfying coarse aggregate requirements.

Broader Implications

Creativity and resourcefulness are needed to fund and implement low-cost remediation technologies and best management practices for abandoned mines given complications with legal status and uncertain or non-existent ownership. This investigation details an effort to investigate the reuse of orphan waste rock, which could be used as concrete aggregate that feeds into green initiatives such as wind turbines. The successful reuse of these materials could result in a double benefit for society: the reduction in cost for remediation is compounded with the reduction in transportation costs for construction. Transportation costs of concrete aggregate are a significant factor in the feasibility of a construction project (ACPA 1993, Chini et al., 2001) and increase the carbon footprint of the project. The construction of an alternative energy project is no exception.

The spirit of this approach and attempt for net improvement in land value aligns with EPA's Brownfields to Brightfields Initiative (U.S. EPA 1999). It also highlights how collaborations among the academic (CSM), non-profit (CCWF), and the private sector (FE) can be used as a model for exploration and solutions to regional environmental problems. From an educational perspective, place-based natural resource decision-making enabled the students to integrate their scientific and engineering findings into recommendations about local planning efforts and hence increased overall satisfaction with a hands-on learning experience (Daniels and Walker 2001). Furthermore, implementation through undergraduate field session provided training to a talented young group of undergraduate students who will begin to enter the workforce as engineering practitioners in 2011. Student responses relating to Field Session 2010 were overwhelmingly positive with comments such as "I learned a lot of things I could have not learned in the classroom", "working in teams in a more independent, [but supportive] environment was really helpful" and "the time in the field and working for an actual company with real world applications was effective for promoting learning."

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